A physical particle model of morphogenesis

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ABSTRACT

This paper describes an evolutionary process which produces dynamic biologic-like patterns. Simulation and visualization of the development of cell populations has many applications. For example, developmental biology and computer graphics. Physically-based particle models are efficient to simulate the dynamical behavior of real life objects. In this article, we propose to model the growth of a biologic tissue using sets of interacting physically-based particles to represent cells, which ad interact to form a tissue.

Keywords
Developmental models, morphogenesis, physically-based particles, animation.

1. INTRODUCTION

Diversity of natural shapes and dynamics may probably explain the endeavors to synthesize biologic-like patterns. However, morphogenesis is extremely complex and involve a wide range of the known genetic and generic cellular processes ([NC90a]).

The present paper illustrates our conviction that it can be represented by means that are not a mapping of natural behavior, particularly genetic algorithms.

A modeling main difficulty is to extract the critical properties leading to the phenomena ([LF97a]). Our approach was, rather than trying to build an ideal representation of the biologic cell -as a mapping of the known cellular behavior- but to progressively add some new properties to an elementary brick -we call it cell-, from which a population emerge a life-like structure.

2. CORDIS ANIMA

The formalism used to describe the model is briefly presented in this chapter. Cordis Anima provide a generic framework to describe and to simulate physically-based particle models. Further information can be obtained in the literature ([LJFCR91a]).

Complex objects are modeled by assembling two elementary atoms, inertial components MAT and interaction components LIA, resulting in a network where nodes are MAT and arcs are LIA.

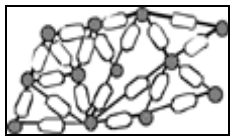

Figure 1 MAT and LIA network.

On the network of the Figure 1, gray circles are MAT and white boxes are LIA.

A MAT atom represents a punctual mass. The MAT algorithm performs the simulation of the mass dynamic: from a force in input, it computes the mass position according to Newton's second law and Euler's sampling scheme.

LIA denotes an interaction between two MAT. From the position and velocity of the masses, it produces two opposite forces of same intensity, in order to respect the action-reaction's principle. The norm of these forces depends on the type of LIA involved.

In the rest of this article, we assume that forces are attractive when intensities are negative.

WSCG POSTERS Proceedings
WSCG'2003, February 3-7, 2003, Plzen, Czech Republic.

3. THE MODEL

3.1 Construction

The model is now presented in detail.

One of the main difficulty of this modeling is to design an efficient intercellular interaction that allows the self-construction of "groups of cells". First we define the kinds of elements involved and then, how they interact. Cells are build to hold necessary and sufficient properties allowing the emergence of "life-like" patterns.

3.2 Elements

3.2.1 MAT

MAT modules compose the level 0. Parameters are masse *M* and position *P*. At this level, MAT are independents.

3.2.2 Cells

Level 1 is made of interacting MAT (level 0 elements). We use the word **Cell** to denote the elementary bricks of the structure. Interactions are then called **intracellular**.

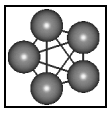

Figure 2 Pentagonal cell.

Figure 2 represents a single hexagonal cell. Masses are visualized as spheres and intracellular interactions as lines. Inside a cell, each MAT interact with the others, resulting in an *agglomerate.*

3.2.3 Population

At this level, we call **Population** the agglomerate of cells (all cells interacting with each others). The interactions connecting two cells are called **intercellular**.

The tissue morphology *emerges* at this stage.

3.3 Interactions

3.3.1 Intracellular

The intracellular (Figure 3) interaction is an unbreakable spring: a linear visco-elastic interaction characterized by its elasticity, its viscosity and its rest length. Tension of the springs minimizes the number of rest positions and gives to the cell a regular aspect (triangle, quad, pentagon…).

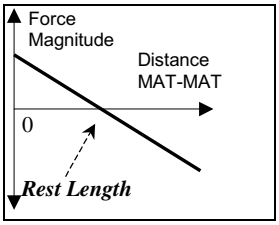

Figure 3 Intracellular interaction.

3.3.2 Intercellular

The interaction operating at this stage ensures the cell adhesion, on which the tissue morphology greatly depends.

We believe that the observed behavior of a teared tissue, which does not re-adhere itself, is critical.

The intercellular interaction (Figure 4) is then composed of a repulsive area, the "Final knock", which ensures the cell its homeostasis, a "Cohesion Field" which allows the cells to adhere themselves, and the "Initial knock" which makes unattached cells able to adhere only if they bear a sufficient energy.

Six 2D points are used to control the intercellular interaction.

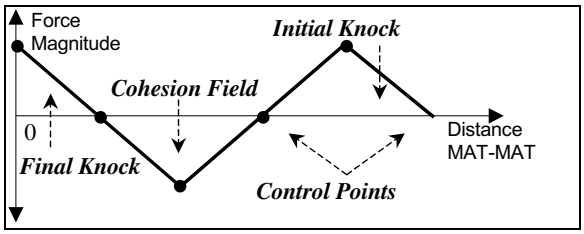

Figure 4 Intercellular interaction.

3.4 Evolutions of the Interactions

In order to generate dynamic patterns, the cell must be able to multiply, position in the tissue and bear energy. Thus, the notion of evolving interactions along with the cell evolution has been added.

3.4.1 Germination

Generating a germ in a mother cell creates a new cell. *Germs* are cells with intracellular interaction length at rest set to zero and masses condensed on a point.

Migration occurs when the germ moves from its initial position to the place where it will grow. It is achieved by setting interactions between the *germ* and the rest of the population to a simple repulsive interaction.

This mechanism leads to the self-positioning of the *germ* within the cell population. The *germ* move until it finds a location where the influences of the other cells are minimal. The duration of *migration* can be predefined, randomly generated or chosen after tests on *germs* external constraints.

3.4.2 Growth

The cellular *growth* begins when migration is over. During this stage, the cell expands into the extra cellular matrix.

Energy is brought by changing the rest length of the intracellular interaction from zero to a high value called *growth* length. While growing, the cell bears

sufficient energy to overcome the "Initial knock" and adhere to other cells.

3.4.3 Freeze

However the effective lengths of the intracellular interactions are not going to reach *growth* lengths. They are threshold to *freeze* lengths. Cell will take its final form, depending on *freeze* lengths and on external constraints.

3.4.4 Cell Attachment

Finally, cell attachment is achieved by both the intracellular and intercellular interaction changes that occur during cell evolution (Figure 5 and Figure 6).

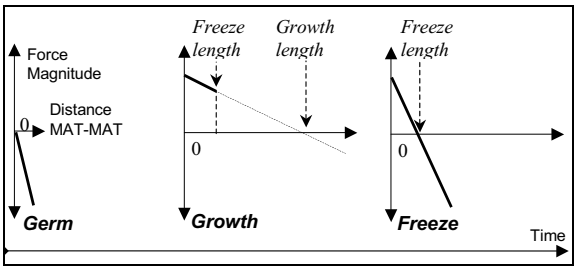

Figure 5 Intracellular interaction evolutions.

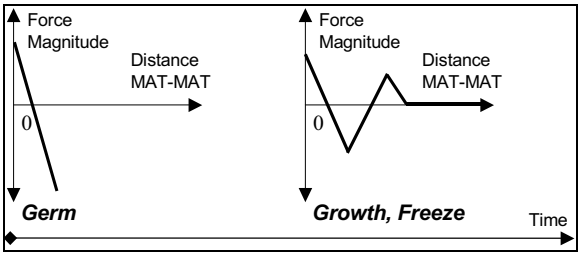

Figure 6 Intercellular interaction evolutions.

4. MODEL SIMULATION RESULTS

Parameterized simulations of the model leads from a growing population to the emergence of groups of cohesive cells sharing a common fate. As long as they are bound together, they behave as a single, highly deformable rigid body. We present some of our simulations results in this section.

4.1 Remarkable Morphologies

Many different morphology of tissues may emerge. An example is the two dimension chain of cells, observed when each cell is bound to two neighbors except the first and last.

On Figure 7, a chain is formed by four *triangular* cells and one *pentagonal* cell.

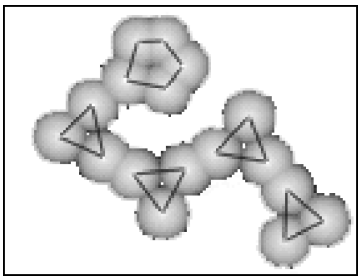

Figure 7 Five cells chain.

Often two or more of these chains merge into a larger new one, since newly created cells can bind themselves to the chain.

On Figure 7, 8 and 9, three steps of the same simulation are considered to observe the formation of a life-like structure.

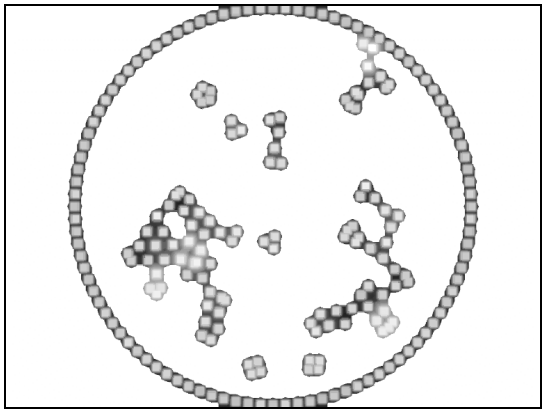

Figure 8 Some cellular chains.

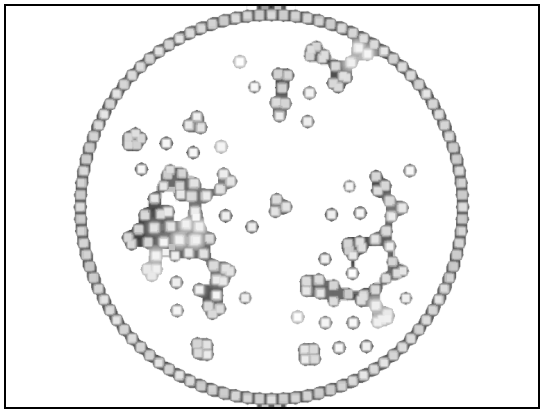

Figure 9 Germination of new cells.

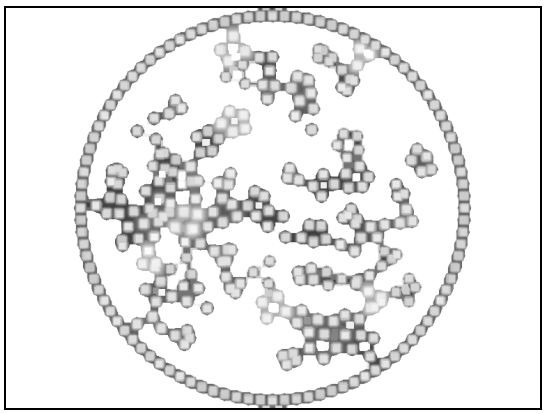

Figure 10 Bounded chains.

4.2 Patterns Visualization

In the lack of a formal measurement of what makes two shapes or patterns look alike, one must rely on visual inspection to validate the model ([Pru93a]). For that reason, we experienced different visual representation.

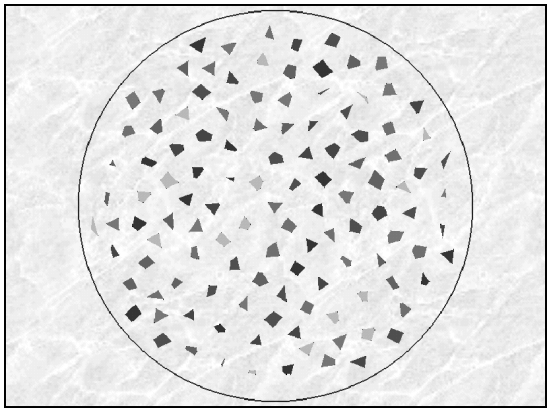

Figure 11 Facet representation of the cell.

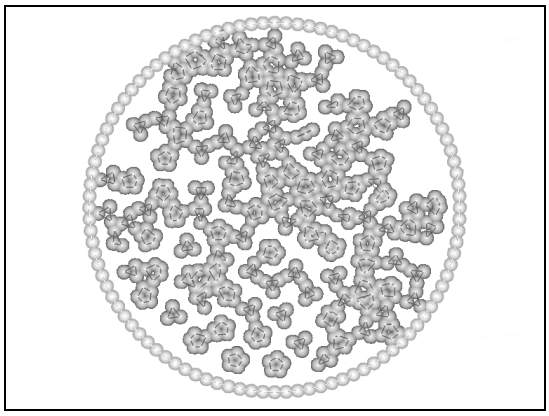

Figure 12 Spheres and lines visualization.

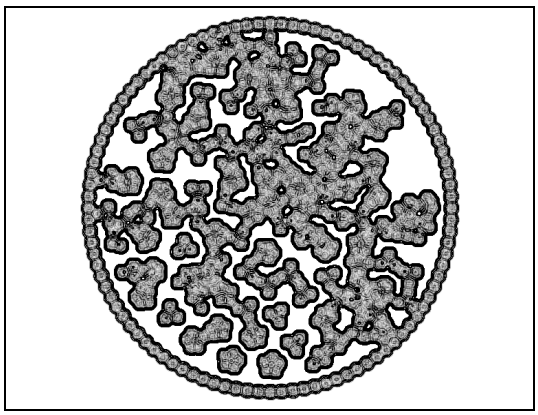

Figure 13 Another visualization of the same structure (cf. Figure 11).

The same simulation, changing only visualization, has produced the forms of Figure 11 and Figure 12.

5. CONCLUSIONS

Modeling morphogenesis with physical principle rather than genetic algorithm is an original approach. In this paper, we propose a physically-based particle model of morphogenesis. We tried to keep it *minimal* but also *generic* to allow an intuitive concept, a high level of control and a wide range of cellular patterns simulation.

Animations obtained have showed that this modeling allows the emergence of dynamic life-like patterns. Some examples of these patterns are presented in the figure of this poster.

6. REFERENCES

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